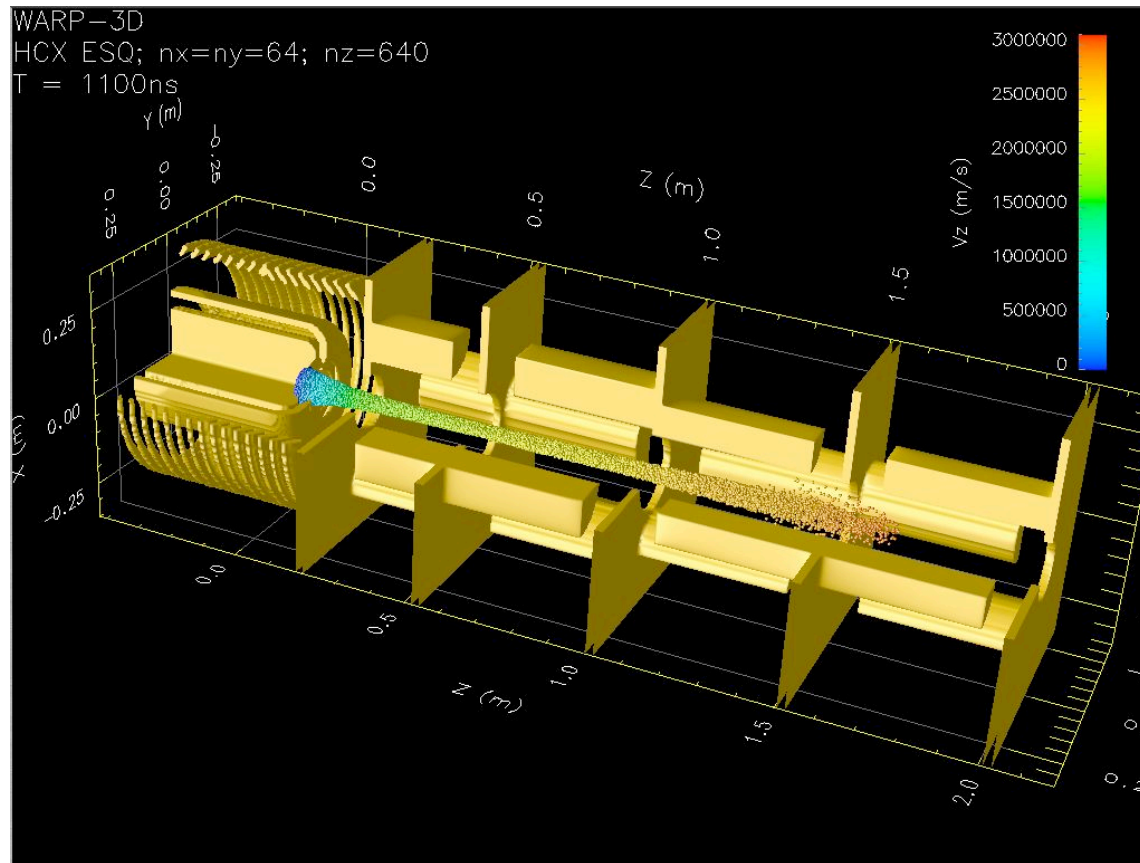# Overview of Warp, a simulation code for studies of intense ion beams and plasmas

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The Heavy Ion Fusion Science Virtual National Laboratory

Warp combines features of a plasma simulation and an accelerator code

Particle-in-cell with several self-field models (explicit or implicit electrostatic, explicit electromagnetic)		
WARP3d x, y, z, p_x, p_y, p_z warped Cartesian	WARPrz r, z, p_r, p_θ, p_z	WARPxy x, y, p_x, p_y, p_z

"lattice" of focusing, bending, and accelerating elements			
sharp edged	axially varying multipole moments	data on a 3D grid	first-principles electrostatic elements at subgrid scale

user-programmable interpreter interface (Python)

parallelization and advanced algorithms

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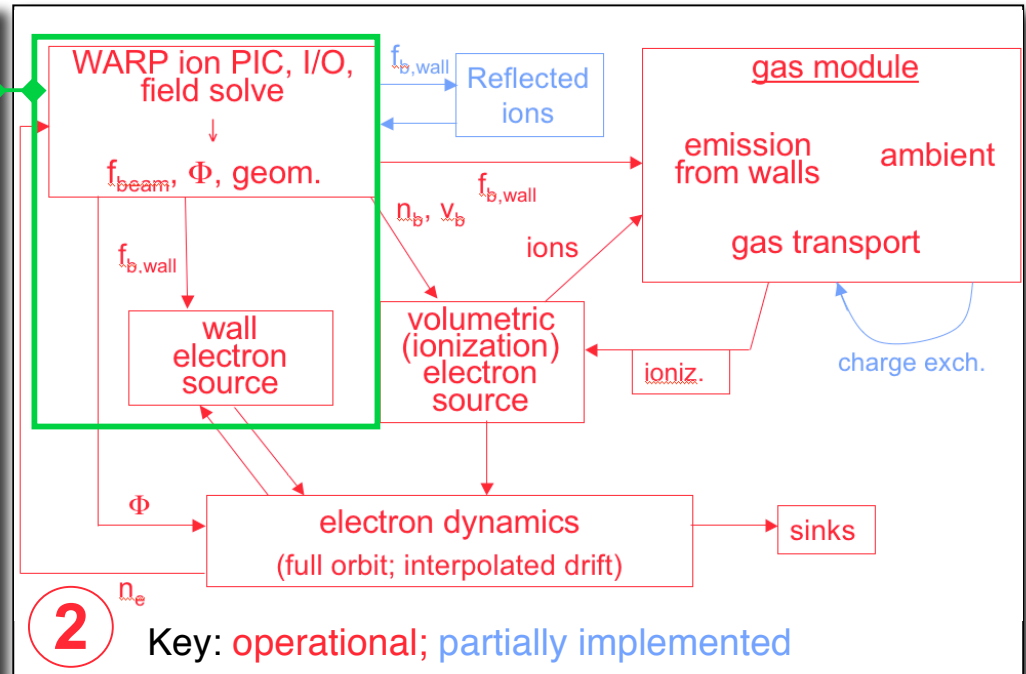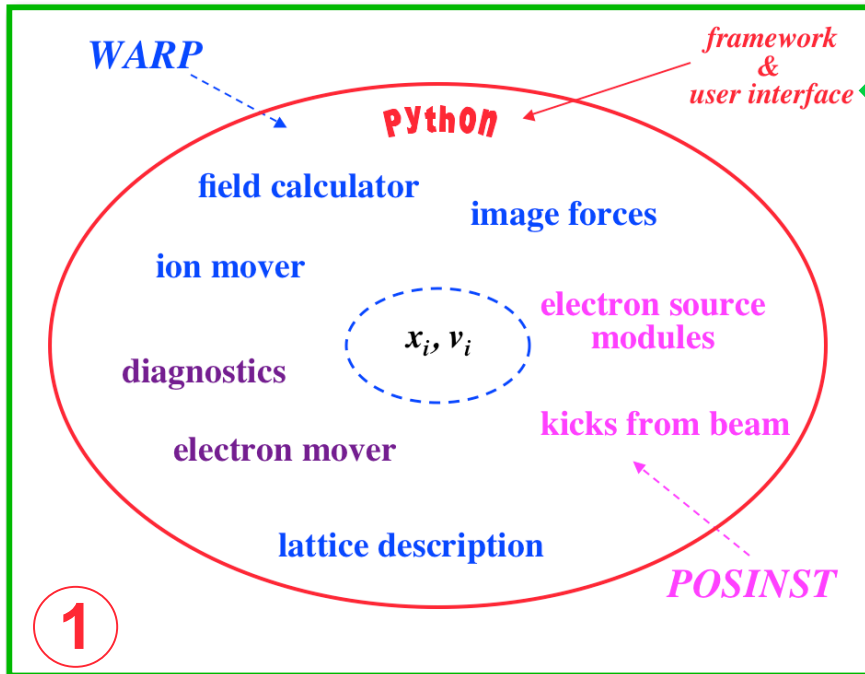
Key aspects of Warp

- **Techniques**
  - "Warped" Cartesian mesh allowing simulations of bent beam lines
  - Time is independent coordinate for particle motion
  - Adaptive Mesh Refinement (AMR) and cut-cell boundaries
  - Large Δt algorithms
  - Boosted frame
  - Time-dependent and steady-state modes
  - Parallel processing
- **Capabilities**
  - Time-dependent space-charge limited injection, inc. AMR
  - Secondaries, ionization, Coulomb collisions
  - Arbitrary applied fields in space and time
  - Overlapping beam-line elements
  - Non-paraxial treatment
  - "Quasi-static" mode for long-term simulations of electron cloud effects

WARP-POSINST unique features

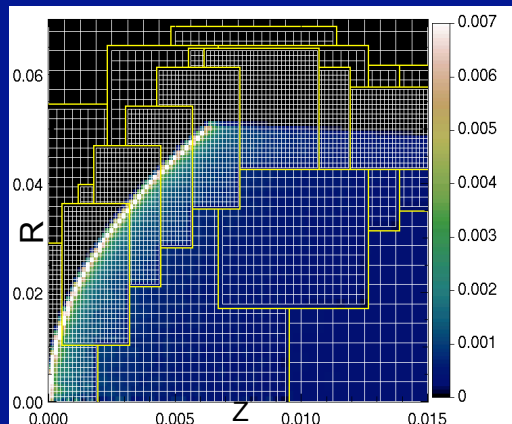merge of WARP & POSINST   +   new e⁻/gas modules

Panel 1

WARP

python — *framework & user interface*

field calculator

image forces

ion mover

x_i, v_i

electron source modules

diagnostics

kicks from beam

electron mover

lattice description

POSINST

①

Panel 2

WARP ion PIC, I/O, field solve
↓
f_{beam}, Φ, geom.

$f_{b,wall}$ → Reflected ions

gas module

emission from walls   ambient

$f_{b,wall}$

n_b, v_b $f_{b,wall}$

ions

gas transport

$f_{b,wall}$

wall electron source

volumetric (ionization) electron source

ioniz.

charge exch.

Φ

electron dynamics
(full orbit; interpolated drift) → sinks

n_e

② Key: operational; partially implemented

Panel 3

+ Adaptive Mesh Refinement

concentrates resolution only where it is needed

Speed-up

③ x10-10⁴

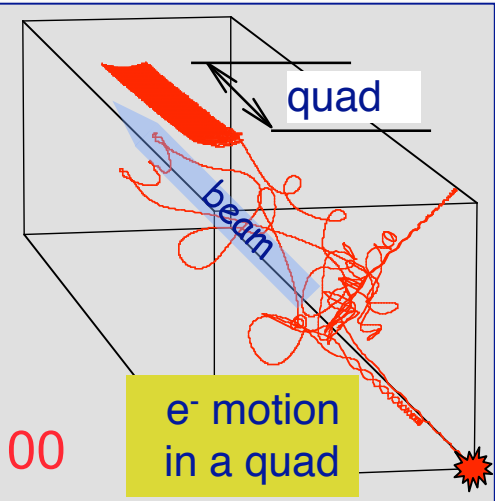R / Z plot with scale 0.00–0.007; axes R (0.00–0.06) and Z (0.000–0.015)

Panel 4

+ Novel e⁻ mover
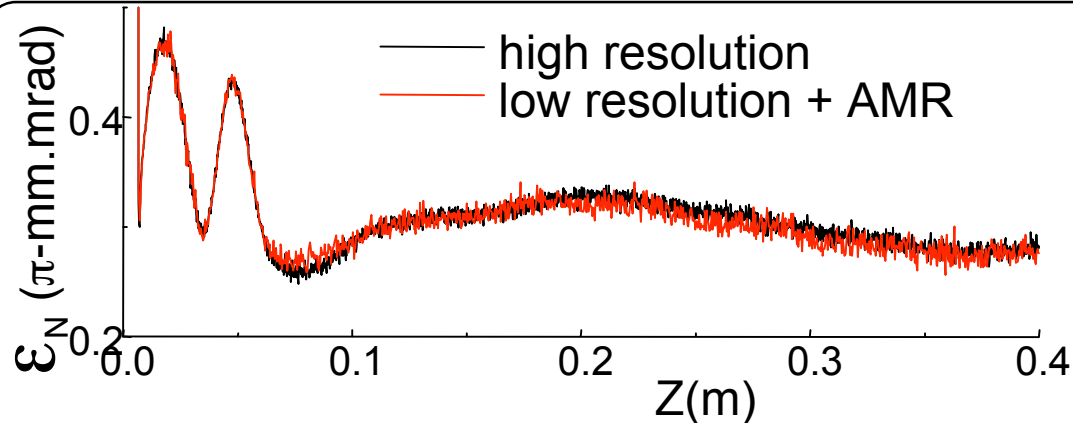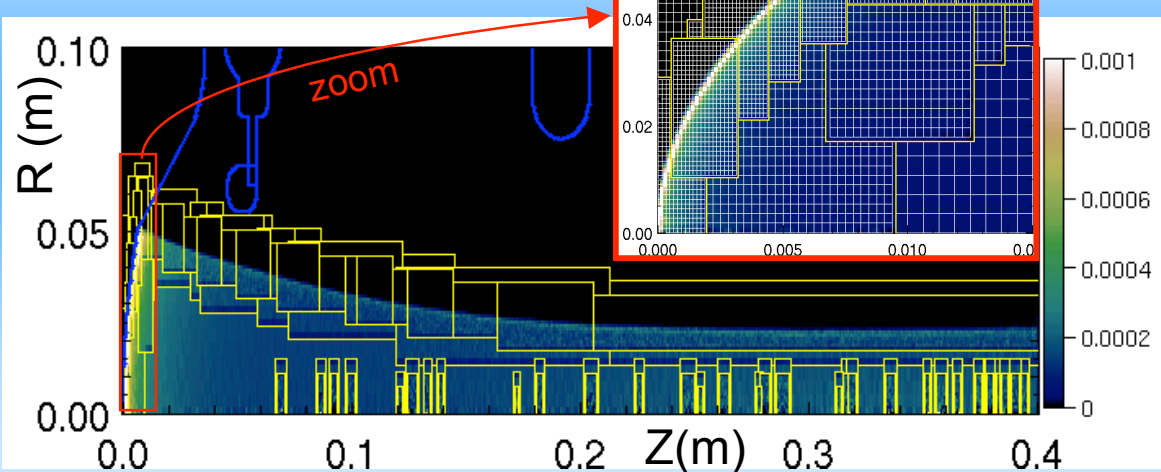
Allows large time step greater than cyclotron period with smooth transition from magnetized to non-magnetized regions

quad

beam

e⁻ motion in a quad

④ Speed-up x10-100

Particle-In-Cell simulation with Adaptive Mesh Refinement

AMR modeling of an HIF source and triode region in (r,z) geometry

- **In this modest (r,z) example, we obtain a ~ 10x savings in computational cost for the same accuracy**

- **AMR implemented in 2-D and 3-D geometries**
- **Parallelization of MR follows decomposition of the base grid**
- **E-M mesh refinement in development**